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Spectral reconstruction of the flash X-ray generated by Dragon-I LIA based on transmission measurements*

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The Dragon-I linear induction accelerator (LIA) at China Academy of Engineering Physics generates 20 MeV flash X-rays mainly for radiography applications in fluid dynamics. Its spectral information is quite important for diagnostic X-ray imaging applications, but because of its short pulse and great radiation intensity, direct measurement is impossible. In this work, we propose a new method based on transmission measurements to obtain the flash X-ray spectrum. Pure iron cylinders were used as attenuation material, and alanine dosimeters were attached on their rear bottom to record the dose after different degrees of attenuation. Iterative least square method was used to unfold the spectrum, while Geant4 Monte Carlo code was used to simulate the X-ray spectrum. The unfolded spectrum and the simulated spectrum have a high degree of consistency, with the reduced chi-square value of 0.044. This shows that the method is reliable in estimating megavoltage high-intensity X-ray spectrum.

Keywords: X-ray spectra, Dragon-I, Spectral reconstruction, Transmission measurements, Geant4

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I. INTRODUCTION

The Dragon-I LIA at China Academy of Engineering Physics (CAEP) can produce high- quality 20 MeV electron beams, in beam current of over 2.5 kA, pulse width of 60 ns and focal spot size of about 1.5 mm. By bombarding high-Z targets it can generate high-intensity flash X-rays of up to 20 MeV by bremsstrahlung. The flash X-rays are quite good for radiography applications in fluid dynamics area [1, 2]. The flash X-ray spectrum is an important parameter for X-ray imaging diagnostic such as beam-hardening correction, dose deposition calculation, duel-energy material detection, and so on. Due to the short pulse width and great radiation intensity, the X-ray spectrum cannot be measured by traditional ways. It is either obtained from simulation, or measured with a large error depending greatly on a guess spectrum [3–5]. In this work, we propose a new method to measure the X-ray spectrum correctly based on transmission measurements.

II. METHOD

Traditional multichannel spectroscopy is not suitable for the high-intensity X-rays. Because of the great pulse accumulation, the pulse height information representing the photon energy cannot be determined correctly. The X-rays are emitted in just tens of nanoseconds, the electronics system cannot acquire all the pulses information in such a short time. Thus, indirect methods have to be used for high-intensity X-ray spectroscopy. Currently transmission measurement is a principal method for measuring high-intensity X-ray spectrum [6–13]. This method is relatively easy and can be applied in the wide range of photon energies.

For n layers of pure attenuation materials, when X-ray traverses one of them, the transmission function is

$$I(h) = \int_{E_{\min}}^{E_{\max}} X(E)E\mathrm{e}^{(-\mu(E)h)}\mathrm{d}E, \tag{1}$$

where $I(h)$ is intensity of the transmitted X-rays, E is X-ray energy, $E_{\max}$ and $E_{\min}$ are the maximum and minimum energy, $X(E)$ is the photon counting spectrum, $\mu(E)$ is the linear attenuation coefficient of X-rays in the material, and h is thickness of the material layer. By defining $R(E,h) = Ee^{-\mu(E)h}$, Eq. (1) can be written as

$$I(h) = \int_{E_{\min}}^{E_{\max}} X(E)R(E,h)\mathrm{d}E. \tag{2}$$

After discretization, Eq. (2) becomes

$$\boldsymbol{I}(h_j) = \sum \boldsymbol{R}_{(i,j)}\boldsymbol{X}_j \quad (i = 1, 2, \ldots, m; j = 1, 2, \ldots, n), \tag{3}$$

where $\boldsymbol{R}_{(i,j)}$ is the response matrix, and m is the discrete points of the X-ray counting spectrum $\boldsymbol{X}$. $\boldsymbol{R}_{(i,j)}$ can be calculated with the X-ray linear attenuation coefficients and the thickness, and $\boldsymbol{I}(h)$ can be measured. Now the problem is how to solve the spectrum $\boldsymbol{X}$ through the known $\boldsymbol{R}$ and $I(h)$ in the linear system of Eq. (3).

However, Eq. (3) is ill-conditioned, and usually n is far less than m, limited by experiment conditions. It cannot be solved directly. In this work, we unfold the spectrum based on

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MLEM algorithm [14], the idea is to get the spectrum closest to the measured data. The squared residual error

$$\boldsymbol{S} = \|\boldsymbol{I} - \boldsymbol{R}\boldsymbol{X}\|^2, \tag{4}$$

must be minimized, based on the least squares method, it can be changed to the regularized equations

$$\boldsymbol{R}^{\mathrm{T}}\boldsymbol{I} = \boldsymbol{R}^{\mathrm{T}}\boldsymbol{R}\boldsymbol{X}, \tag{5}$$

where $\boldsymbol{R}^{\mathrm{T}}$ is the transpose matrix for $\boldsymbol{R}$. Assuming $\boldsymbol{N} = \boldsymbol{R}^{\mathrm{T}}\boldsymbol{I}$ and $\boldsymbol{A} = \boldsymbol{R}^{\mathrm{T}}\boldsymbol{R}$, we have

$$\boldsymbol{N} = \boldsymbol{A}\boldsymbol{X}. \tag{6}$$

Iteration methods can be used to solve Eq. (6) to get X-ray photon counting spectrum $\boldsymbol{X}$.

III. EXPERIMENTAL

A. Simulation

The process of 20 MeV electron beams bombarding tantalum targets to produce high-intensity flash X-rays can be simulated by Monte Carlo particle transport simulation tools such as Geant4 [15–17], MCNP [18] and FLUKA [19], based on geometrics of the real experiment environment (Fig. 1(a)). In this paper, Geant4 (10.00.p02 version) was used. The simulation was done with 5×10^8 electrons at 20 MeV. The X-ray photons were collimated by stainless steel collimators. Some of them enter the detection area, and the counting spectrum is shown in Fig. 1(b).

It can be seen that the counts are mainly in energy range of < 5 MeV, above which they change slowly. Some fine structure can be seen at 0.511 MeV and below. This helps the X-ray spectrum reconstruction. The green and red lines represent trajectories of photons and electrons, respectively.

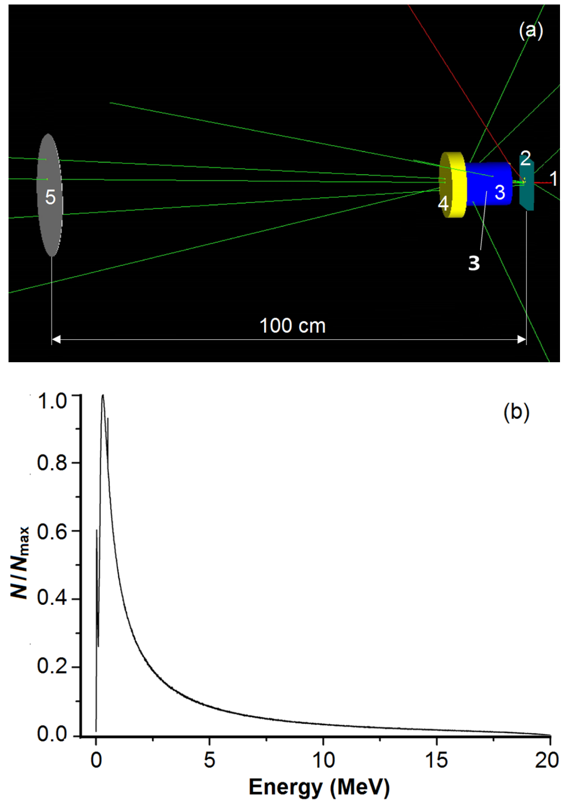

Fig. 1. (Color online) Geometry (a) and results (b) of the Geant4 simulation. The flash X-ray counts were normalized to the maximum count 1, 20 MeV electron beam; 2, the target made of 24 tantalum foils of 50 µm thick and placed in 0.5 mm intervals; 3, cylindrical stainless steel collimator of 10 cm inner diameter and 0.25 cm wall thickness (it was assumed as pure iron in the simulation); 4, PMMA shielding to stop escaping electrons; 5, area of detection. Green lines, trajectories of the photons; red lines, trajectories of the electrons.

B. Measurement

Pure iron was used as attenuation material and the attenuation dose was measured by alanine dosimeters. An epoxy frame was used to hold 12 iron cylinders in lengths of 2.1, 6.0, 10.3, 15.0, 20.2, 26.2, 33.1, 41.2, 51.2, 64.0, 82.2 and 113.3 mm (Fig. 2). The alanine dosimeters were stuck on rear bottom of each iron cylinder. Alanine dosimeter is not energy-dependence above 100 keV, being suitable for MeV flash X-ray detection. Its dose readings are of good linearity over a wide dose range of 10–2×10^5 Gy, with an overall measurement error of less than 5%. These are helpful for the spectrum unfolding algorithm [20].

Dosimetry measurements of the high-intensity flash X-rays penetrating Fe cylinders of different lengths were performed on the Dragon-I LIA at CAEP. ESR (electron spinning resonance) reading of the alanine dosimeters was done at CUST. The results are shown in Table 1. The alanine dosimeters for

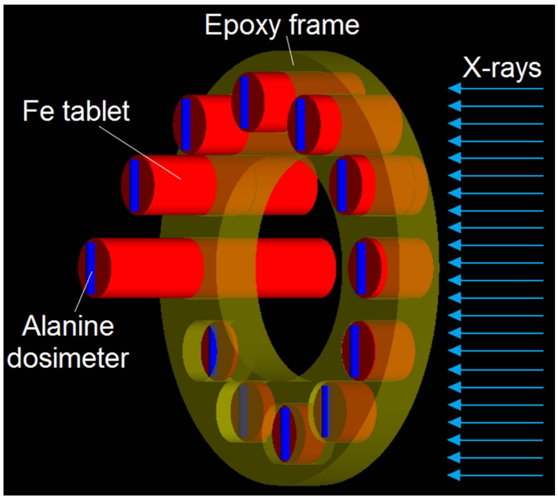

Fig. 2. (Color online) Schematic view of the epoxy frame (a) to hold the iron tablets.

TABLE 1. Dose readings of alanine dosimeters for Fe cylinders of different lengths

Length (mm)	2.1	6.0	10.3	15.0	20.2	26.2	33.1	41.2	51.2	64.0	82.2	113.3
Dose (Gy)	610	190	126	119	107	95	83	73	56	41	36	30

the Fe tablets in lengths of 2.1 and 6.0 mm show extraordinary high dose readings, as the two Fe cylinders were too short to stop the electrons escaping from the PMMA shielding. Therefore, just the 10 dose readings for the Fe tablets of longer than 10 mm were used for spectrum unfolding.

IV. RESPONSE MATRIX

To solve the discrete X-ray spectrum $X_i (i = 1, 2, \ldots, m)$ in Eq. (3), accuracy of the response matrix $\boldsymbol{R}_{(i,j)}$ is important. The definition of $R(E, h) = Ee^{-\mu(E)h}$ in Section II concerns about just the attenuated incident X-rays. For high energy X-rays induced by 20 MeV electron beams, however, the situation is far more complex. The alanine dosimeters on rear bottom of the Fe cylinders were not only irradiated by the incident X-rays, but also scattered X-rays and electrons generated by the electron pair effect, a photon-materials reaction of the X-rays of ≥ 1.02 MeV. Therefore, the response matrix $\boldsymbol{R}_{(i,j)}$ have to be re-defined. Theoretical calculation of the real $\boldsymbol{R}_{(i,j)}$ is difficult, but Monte Carlo method offers an easy way to calculate it.

If the incident X-ray phones are mono-energetic, one has the following equation

$$R(E_0, h) = I(h)/N, \tag{7}$$

where, N is number of the incident photons in energy E_0 and $I(h)$ stands for the transmitted X-ray intensity, which can be detected by the alanine dosimeters. The Geant4 simulation was conducted with mono-energetic photons at 30 discrete energy points from 0.2 MeV to 20 MeV, so as to calculated energy deposition in alanine dosimeters on rear bottom of the 10 Fe cylinders in lengths of 10.3–113.3 mm. The energy depositions were converted to absorbed doses, and Eq. (7) was used to obtain response of the 10 alanine dosimeters to a particular energy of the X-ray phones. As Fig. 1(b) shows, the simulated X-ray yield changes little in energy range above 5 MeV, and the main peak is below 5 MeV, thus we selected 25 points in the $<$ 5 MeV region, i.e., 0.2, 0.4, 0.6, . . . , 4.8 MeV, and 5 points at 5–20 MeV, i.e., 5, 6, 8, 15 and 20 MeV. A total of 10^9 X-ray photons were simulated for each energy point, and the calculated response matrix was plotted in Fig. 3.

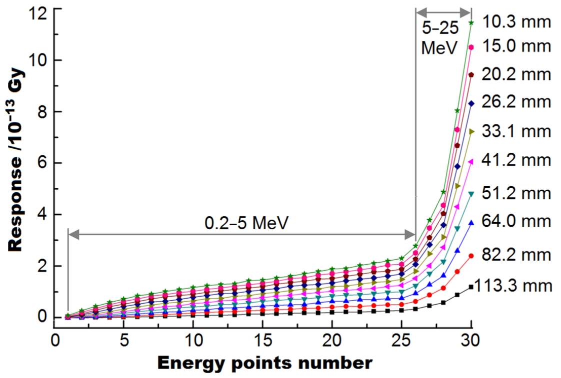

Fig. 3. (Color online) Response of the alanine dosimeters for different energy points and Fe cylinders of different lengths.

V. RESULTS

Using Eq. (3), we unfolded the X-ray spectrum with the dose readings in Table 1, the response matrix (Fig. 3) and the iterative MLEM unfolding algorithm mentioned in Section II. The results are shown in Fig. 4, together with the simulated spectrum in Fig. 1(b). It can be seen that the reconstructed

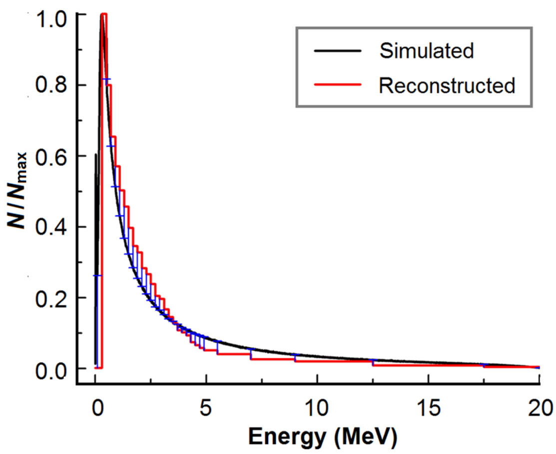

Fig. 4. (Color online) The reconstructed flash X-ray spectrum, compared with the simulated spectrum.

spectrum is in close proximity to the simulated spectrum. The reduced chi-square was calculated as 0.044. The difference between the two spectra can be reasoned as follows. First, the Geant4 simulation was done with simplified experimental conditions, and each parameter was chosen ideally, e.g., the incident electrons are all of 20 MeV energy. However, the real electron beams generated by the LIA have an energy spread around 20 MeV, and it is hard to take this factor into account in the simulation. Imperfection in the unfolding algorithm, and in dosimetry, may be another source of errors. In this work, we unfolded the 30-points spectrum from dose readings of only 10 alanine dosimeters.

VI. CONCLUSION

It is quite difficult to obtain spectral information of high-intensity flash X-ray because of its short pulse width and great radiation dose. Based on transmission measurements, we propose a new method to obtain X-ray spectrum generated by Dragon-I LIA. A PMMA frame was designed to hold all the attenuation materials and dosimeters. The reconstructed spectrum has a high degree of consistency with the simulated spectrum. These prove that the method is reliable in estimating high-intensity flash X-ray spectrum.

The work needs to be improved. More iron cylinders shall be fixed in the PMMA frame, for better quality of spectra unfolding. Different kinds of attenuation material shall be used, such as copper, aluminum and beryllium and more experiments should be done with each attenuation material. This time, we did the work with just 30 discrete energy points, focused in the 0–5 MeV energy region. Later, we will unfold the spectrum with more discrete energy points in the whole 0–20 MeV energy range.

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